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Theoretical study of shock-aerating activator for dry enrichment of constructional materials

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Abstract. For construction in areas remote from the main raw material industrial bases, reconstruction of destroyed objects and infrastructure, roads, especially in mountainous earthquake-prone areas as part of concretes it is advisable to use enriched local natural materials and recycled materials. The most effective method of enrichment is activation of materials by fine grinding. To implement the technology, a new development of small-sized compact activation equipment is proposed, which allows achieving guaranteed strength of concrete while reducing construction time and saving costs for imported materials.

1. Introduction

In the organization of work on construction, repair and restoration of cement concrete coatings for special objects (Federal highways, monolithic structures, industrial facilities, industrial and residential facilities, etc.), increasing the production capacity of the technological equipment used for these purposes is of paramount importance [1, 2].

Currently, expensive domestic and foreign fast-hardening dry mixes (FHM) based on high-grade cements are used for construction, repair and restoration of cement concrete coatings [3]. In addition, FHM are placed in the destroyed coatings of special objects almost manually. This dramatically increases the cost of work at low productivity, which is unacceptable in accordance with the target dates of construction and reconstruction of objects of the same type.

Existing mechanization equipment of these types of work in order to reduce their cost do not permit to use modern energy-saving technologies with the activation of local materials, low-grade cements and production waste at the construction sites for the production of FHM, as well as to conduct a comprehensive mechanization of their production and laying in coatings [4, 5, 6].

Thus, the main technological equipment for grinding and activating constructional materials (clay, gypsum, soft coal, lumpy lime, etc.) are ball drum and high-speed hammer mills [7, 8]. At the same time, the working process is carried out in them by grinding bodies on the principle of crushing and abrasion, which requires sufficiently high energy consumption with a significant material consumption of this equipment (energy costs for grinding reach 30-40 kW h/t).

The main trend of increasing the unit capacity of small-sized grinders is to increase their geometric dimensions, which at the same time causes significant problems due to general reliability decrease, complication of the work of bearing units and drive structures. The total weight of the equipment for activation and dry enrichment of concrete and cement aggregate is from 43 to 150 tons, and a significant part of the metal (from 1 to 3 kg per 1 ton of cement) is lost irrevocably due to abrasive and corrosive wear of grinding bodies and lining of working bodies of ma-chines.

The purpose of the study is to develop a compact impact-aerating activator of dry-enrichment of local construction materials that meets the requirements of the finished product dispersion, has high performance, provides normal operation of the production line and has a relatively low energy consumption and weight for use in mobile performance.

2. Material and Methods

Table 1. Operations and modes of the dynamic air-dry enrichment of materials

Operation name	Brief characteristic	Operation name
Contaminated grain of cement	Base material, particle with size of 30-60 microns with an oxidized surface	Contaminated grain of cement
Drying		Drying
(heating to t > 100 ºC)	Moisture removal. Hydrophobization and shrinkage of impurities (increasing resistance to air moisture by introducing special additives that hydrophobize the grain surface)	(heating to t > 100 ºC)
Directed impact with speed V ≥ 30 m/s	Mechanical removal of unbound moisture, partial removal of small and dusty particles	Directed impact with speed V ≥ 30 m/s
	Destruction of weak grains, cleaning the grain surface, dust removal	
Operation name	Brief characteristic	Operation name
Contaminated grain of cement	Base material, particle with size of 30-60 microns with an oxidized surface	Contaminated grain of cement
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Quantitative estimation of the efficiency and operational properties of activation equipment is determined by the ratio of material costs to the production unit, which is expressed by the following indicators:

- specific power consumption of the equipment Wspec (characterizes the amount of input energy N, related to productivity Q of the equipment);

- specific metal content Mspec (is characterized by the ratio of the mass of the equipment M to its productivity Q);
- relative wear Ispec (is characterized by the ratio of wear rate of the working bodies and grinding bodies I to mass Gm of finished product of grinding);
- an integral indicator of efficiency, which is the basis for establishing links between individual specific indicators – specific energy intensity and specific productivity Pspec.

The small-sized equipment proposed by the authors includes an aerodynamic activator of reduced energy intensity (3.3 kW h/t) with a mass of 300 kg and a mobile mixing and laying installation, the use of which allows to produce FHM and mechanize the work on their laying using local materials, low-grade cements and sands [8].

The decision on rational parameters and performance characteristics of the designed aeroactivator is based on a physical and mechanical model of impact separation of the surface layer of contaminants from cement particles (Table 1).

The purpose of calculating the rational parameters of the activator is to achieve quality indicators of cement:
- absence of contaminating surfaces;
- mechanical removal of unbound moisture;
- partial removal of small and dusty particles;
- increase of the specific surface area of the cement particle.

3. Results and Discussions

To calculate the activator parameters, we consider the following physical model for cleaning cement grains (particles) from the contaminating surface. The interaction of contaminants with particles is characterized by bound properties, i.e. their ability to resist separation from cement particles. It is known [9, 10] that cements lose about 10-15% of their activity within a month after their manufacture. During long-term storage, the greatest loss of activity is shown by binders with a higher specific surface area (high-temperature and fast-hardening). It was found that stale cements have low rates of early strength gain due to the effect of vaporous water and air carbon dioxide on cement particles (water absorption increases by 3% after 30 days, and the strength decreases by 37 MPa). The strength decrease is compensated by an increased consumption of cement – from 5 to 20%.

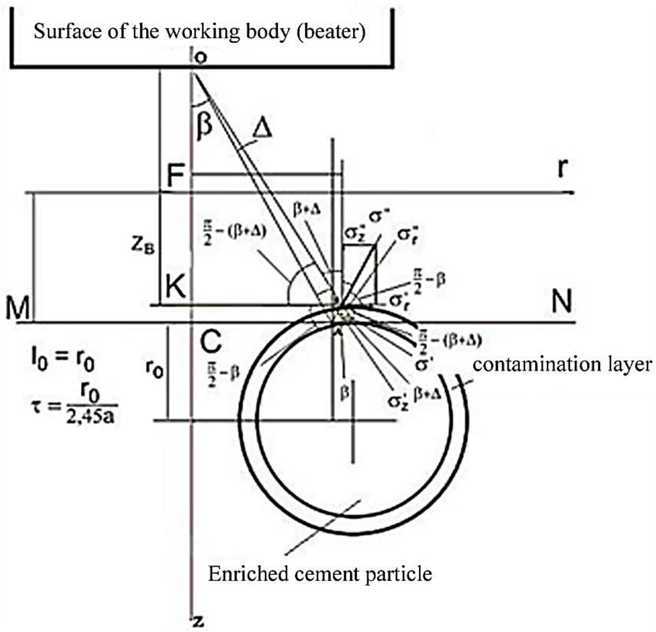

Figure 1. Calculation scheme for determining the resulting stress in the contamination layer of the cement particle

Figure 1 shows a calculation scheme for determining the resulting stress of the surface layer of contaminants caused by the action of a longitudinal wave propagating into the array of a spherical particle with a radius r_o when it hits the surface of the working body (beater) at any point «*O*». In general, when the boundary of the particle reflection from the surface of the beater is an arbitrary angle, the total mechanical stress in the vicinity of the impact point under the influence of direct and reflected pulses is determined by the area enclosed between the traces of the treated surface and the reflection surface.
In this case, the duration τ of the particle heating time to a depth equal to l_0, is defined by the expression:

$$\tau = \frac{r_0^2}{2.45\alpha},$$

where α – thermal conductivity ratio of cement, (W/(mK)).

Select the coordinates of point *A* on the trace of the reflection plane *MN*, equal to $r_A = r_0$ and $z_A = r_0$, then find the angle β, at which the direct pulse *OA* falls on the boundary of the reflection plane *MN*, from the expression:

$$tg\beta = \frac{AC}{OC} = \frac{r_0}{2r_0} = 0.5$$

and $\beta = arctg0.5 = 26.57°$.

Select point *B* that lies on the beam of a direct pulse directed at an angle $\beta + \Delta = 30°$ $(\Delta = 30° - 26.57° = 3.43°)$ to boundary *MN*. From point A we draw the pulse reflected from boundary MN at an angle $\left(\frac{\pi}{2} - \beta\right)$ equal to the angle of incidence $\angle OAC$ up to the intersection with the beam directed from point *O* at an angle $\angle(\beta + \Delta)$ to the axis *z*.
This intersection will occur at point *B*, which has coordinates:

$$r_B = KB = OB \cdot \sin(\beta_1 + \Delta) \quad (1)$$

$$z_B = OK - r_0 = OB \cdot \cos(\beta + \Delta) - r_0 \quad (2)$$

From consideration of ΔOAB we have $\frac{OB}{\sin 2\beta} = \frac{OA}{\sin(2\beta + \Delta)}$ from which

$$OB = \frac{2r_0 \cdot \sin 2\beta}{\cos\beta \cdot \sin(2\beta + \Delta)} \quad (3)$$

After substituting values *OB* from (3) into expressions (1) and (2), we get formulas for determining the coordinates of point *B*:

$$r_B = \frac{2r_0 \sin 2\beta \cdot \sin(\beta + \Delta)}{\cos\beta \cdot \sin(2\beta + \Delta)} \quad (4)$$

$$z_B = r_0\left[\frac{2\sin 2\beta \cdot \cos(\beta + \Delta)}{\cos\beta \cdot \sin(2\beta + \Delta)} - 1\right] \quad (5)$$

After substituting the values of trigonometric functions of angles in expressions (4) and (5), we obtain:
$r_B = 1.071r_0$; $z_B = 0.854r_0$.

At point *B*, the stresses σ^1, originating from the pulse coming from the actual perturbance source (point *O*) and the stress σ^{11}, originating from the pulse coming from the fictitious perturbance source (point O', which is located at a distance of $2r_0$ from point *C*) must be summed up.

Resolved stress from the effect of both waves is determined from the ratio

$$\sigma_\Sigma = \sqrt{\sigma_{zz}^2 + (\gamma\sigma_{rr})^2} \tag{6}$$

$$\sigma_{zz} = \sigma_z^1 - \sigma_z^{11} \tag{7}$$

$$\sigma_{rr} = \sigma_r^1 + \sigma_r^{11} \tag{8}$$

where γ – Poisson's ratio.
According to the scheme (see fig. 1) using geometric transformations, we define the following values:

$$\sigma_z^1 = \sigma^1 \cos(\beta + \Delta);\ \ \sigma_z^{11} = \sigma^{11} \cos\beta \tag{9}$$

$$\sigma_r^1 = \sigma^{11} \cos\left(\frac{\pi}{2} - \beta\right);\ \ \sigma_r^{11} = \sigma^1 \cos\left[\frac{\pi}{2} - (\beta + \Delta)\right] \tag{10}$$

The direct pulse to point B comes with the amplitude at the front

$$\sigma^1 = \sigma_0\left(\frac{r_0}{OB}\right)^{\varepsilon} \cdot \cos(\beta + \Delta)\exp\left(-\frac{\rho v}{m}\Delta t\right) \tag{11}$$

where $\varepsilon = 2 - \left(\frac{\gamma}{1-\gamma}\right)$ – the attenuation factor (in our case, for $\gamma = 0.18$, the value of the attenuation factor will be $\varepsilon = 1.78$); m – the mass of the striking body per unit area of its cross section in the direction of impact, $m = M/S$; v – the transfer rate of elastic waves in the cement particle;

Δt – the time after passage of the direct pulse front at point B and the arrival of the reflected pulse front, determined by the dependence:

$$\Delta t = \frac{OA + AB}{C} - \frac{OB}{C} \tag{12}$$

Let's determine the length of the segment AB based on the sine theorem from the same triangle (ΔOAB):

$$\frac{AB}{\sin\Delta} = \frac{l_0 + r_0}{\cos\beta} \cdot \frac{1}{\sin[\pi - (2\beta + \Delta)]} \tag{13}$$

From the expression (13) we have:

$$AB = 2r_0 \frac{\sin\Delta}{\cos\beta \cdot \sin(2\beta + \Delta)} \tag{14}$$

$$OA = \frac{2r_0}{\cos\beta} \tag{15}$$

Taking into account (2), (14) and (15), the expression (12) will take the following form:

$$\Delta t = \frac{2r_0}{v}\left[\frac{\sin(2\beta + \Delta) + \sin\Delta - \sin 2\beta}{\cos\beta \cdot \sin(2\beta + \Delta)}\right] \tag{16}$$

In the expression (16), defining $\left[\frac{\sin(2\beta + \Delta) + \sin\Delta - \sin 2\beta}{\cos\beta \cdot \sin(2\beta + \Delta)}\right] = F(\beta, \Delta)$, we obtain $\Delta t = \frac{2r_0}{v} \cdot F(\beta, \Delta)$. For the specified values of the considered angles, equal to $\beta = 26°34'$, $\Delta = 3°26'$, $\sin\beta = 0.447$, $\sin\Delta = 0.06$, $\cos\beta = 0.894$, $\cos\Delta = 0.998$, $F(\beta, \Delta) = 0.127$.

Then $\Delta t = \frac{0.254 r_0}{v}$.

In expression (11), we define the value $\exp\left(-\frac{\rho v}{m}\Delta t\right)$, where $m = M/S = \frac{4}{3} r_0 \rho_\Pi$

$$\frac{\rho_M v}{m} = 1.5\frac{\rho_M v}{\rho_\Pi r_0};\ \frac{\rho_M v}{m}\cdot\Delta t = \frac{3}{2}\frac{\rho_M}{\rho_\Pi}\cdot F(\beta,\ \Delta) = 0.219;$$

$$\exp\left(-\frac{\rho v}{m}\Delta t\right) = \exp(-0.219) = 0.803;$$

$$\sigma^1 = \sigma_0\cdot\left[\frac{cos\beta\cdot\sin(2\beta+\Delta)}{2\sin 2\beta}\right]^{1.78}\cdot\cos(\beta+\Delta)\cdot 0.803 = 0.179\sigma_0. \tag{17}$$

Stress σ^{11} on the front of the reflected pulse will depend on the outlet angle of the beam *OA* (in this case, the angle β), the path traveled (*OA* + *AB*), and the reflection factor A_{pp} at point *A*, assumed to be equal $A_{pp} = 0.1$:

$$\sigma^{11} = \sigma_0\cdot 0{,}1\left[\frac{r_0}{OA+AB}\right]^{\varepsilon}\cdot\cos\beta \tag{18}$$

Considering (14) and (15) expression (18) will be the following:

$$\sigma^{11} = \sigma_0\cdot 0.1\left[\frac{1}{2}\cdot\frac{\cos\beta\sin(2\beta+\Delta)}{\sin(2\beta+\Delta)+\sin\Delta}\right]^{\varepsilon}\cdot\cos\beta. \tag{19}$$

Substituting the angles values into expression (19), we obtain

$$\sigma^{11} = 0.019\sigma_0. \tag{20}$$

Substituting values (17) and (18) into expressions (9) and (10), we obtain:

$$\sigma_z^1 = 0.179\sigma_0\cdot\cos(\beta+\Delta);\ \sigma_z^{11} = 0.019\sigma_0\cdot\cos\beta;$$

$$\sigma_r^1 = 0.019\sigma_0\cdot\cos\left(\frac{\pi}{2}-\beta\right);\ \sigma_r^{11} = 0.179\sigma_0\cdot\cos\left[\frac{\pi}{2}-(\beta+\Delta)\right].$$

Then expressions (7) and (8) will take the following form:

$$\sigma_{zz} = 0.179\sigma_0\cdot\cos(\beta+\Delta) - 0.019\sigma_0\cdot\cos\beta = 0.179\sigma_0\cdot 0.866 - 0.019\sigma_0\cdot 0.894 =$$
$$= 0.155\sigma_0 - 0.017\sigma_0 = 0.138\sigma_0;$$
$$\sigma_{rr} = 0.019\sigma_0\cdot\cos\left(\frac{\pi}{2}-\beta\right) + 0.179\sigma_0\cdot\cos\left[\frac{\pi}{2}-(\beta+\Delta)\right] =$$
$$= 0.019\sigma_0\cdot 0.447 + 0.179\sigma_0\cdot 0.5 = 0.008\sigma_0 + 0.089\sigma_0 = 0.097\sigma_0.$$

The value of the resolved stress is determined by substituting already known values into the formula (6):

$$\sigma_\Sigma = \sqrt{(0.138\sigma_0)^2 + (0.18\cdot 0.097\sigma_0)^2} = 0.1391\sigma_0.$$

The value of the resolved stress is determined by substituting already known values into the formula. Thus, the destruction of the contaminated surface of the cement particle occurs when the impact velocity *v = 30 m / s* is reached, when the total stresses $\sum\sigma$ exceed its tensile strength $[\sigma_p]$.

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4. Conclusions

Based on the above, we can draw the following conclusions:

1. To solve the problem of increasing the activity of local cohesive («stale») cement), it is advisable to use activation crushing and grinding devices, as well as creating a favorable environment for strength gain (high humidity and positive ambient temperature) immediately before receiving the concrete mixture.

2. The most effective of the existing types and technical solutions for the preparation of activated (concentrated) cements is an aerodinamic impact activator with an increased number of working zones and a rational location of the working body.

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